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RADC-TR-65-514



## **FAILURE MECHANISMS IN RESISTORS**

**F. R. Hand and A. Horberg**

**TECHNICAL REPORT NO. RADC-TR-65-514**

**May 1966**

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# **FAILURE MECHANISMS IN RESISTORS**

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## FOREWORD


This report was prepared by IIT Research Institute, Chicago, Illinois; under Contract Number AF30(602)-3614; System No. 760E; Project No. 5519; and Task No. 551906. The RADC project engineer is Joseph M. Schramp, EMERP.

This is a progress report covering the period of work from 1 June, 1965 to 15 October, 1965; the originator's report number is IITRI E6042.

This report is not releasable to CFSTI because it contains information prohibited from release by AFR 400-10 Strategic Trade Control Program.

This report has been reviewed and is approved.

  
Approved: JOSEPH M. SCHRAMP  
Reliability Physics Section  
Reliability Branch

  
Approved: D. F. BARBER  
Chief, Reliability Branch  
Engineering Division

## ABSTRACT

This report describes some results of research on failure mechanisms in thin metal film resistors. The effort is to develop mathematical expressions for these mechanisms which can be assembled into a comprehensive model for this class of device.

The report describes the early results of analysis of nichrome resistor life test data obtained from a manufacturer of resistive networks. Also presented are the results of computer analysis of Matrix II life test data on Evanohm resistors indicating that the model must contain separable functions of time and the experimental variables (stresses, initial resistance, etc. ). The experimental work described involves an attempt to statistically design an experiment to give the maximum number of degrees of freedom in estimating error and in constructing a model.

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## I. INTRODUCTION

This is the second technical report describing the activities of the staff of IIT Research Institute in a program to develop a comprehensive physical model of the failure mechanisms operating in thin film resistors. This work is being carried out under Contract AF 39(602)-3614 and this report covers the period 1 June 1965 through 31 October 1965.

The current project is part of a broad study of the Physics of Failure in Electronic Components under the directorate of Rome Air Development Center. The objective of the research at IITRI has been to thoroughly investigate the mechanisms operating in thin film resistors in order that mathematical descriptions of these mechanisms can be made which can be combined into a predictive mathematical model for the behavior of the device under operating stress.

We have concentrated our efforts during this program on the planar nichrome thin film resistor, as used in resistor networks and integrated circuits. The first part of this program was concerned with determining the range of alloy compositions distributed through the thickness of these films when deposited from a heated filament loaded with nichrome alloy. We also continued with the investigation of the IRC Matrix II life test data, performing a Taylor's Series expansion of the data. The current status of this work is reported in Section III.

Section I is a discussion of the efforts to acquire life test data on commercial film nichrome resistors and some preliminary results of the analysis of the data received are given.

Section IV describes our efforts to deposit homogeneous films of various compositions of nickel-chromium alloys in order to determine the dependence of rate constants of the failure mechanisms on composition.

## II. DISCUSSION OF MANUFACTURER'S DATA

One of the chief reasons for choosing to experiment with nichrome thin films in this program, in preference to such simpler materials as chromium or tantalum, was the potential availability of life test data from various resistor manufacturers. A number of micro-electronics firms, those making passive networks as well as integrated circuit fabricators, use evaporated nichrome for the resistive elements. These films are deposited in a variety of ways, from filament evaporation of nichrome wire to electron beam evaporation from a large ingot. It is deposited on many different substrates, among them alsigmag ceramic, pyrex glass, and single crystal silicon. So among all of these resistor fabrication systems, it seems evident that there should be ample life test data.

We approached three of these firms, all located in the Los Angeles, California region to provide us with as much data as they have collected in their reliability programs.

Two agreed to supply us with the data in return for being placed on the report distribution list. To date, however, only one of these companies has actually sent its data to us.

The data which have been received represent the testing of 145 resistor networks each containing 7 resistor elements, or more than 1000 individual resistors. Most of these units were tested for periods in excess of 1000 hours so there are roughly  $10^6$  resistor-hours represented by the data. There are two important drawbacks to this data, however. First, all of the tests were made in an ambient temperature of 70°C so there is no way to systematically study the effects of temperature; and second, there are differences of orders of magnitude in the dissipated power density among resistors in the same network under test, but no estimate of the temperature rise associated with each level of dissipation nor an indication of its percentage of rated power from which we could estimate the temperature rise. These deficiencies make these data of little value in trying to derive an empirical model, but they will be useful in verifying the model derived from our own experiments and in acting as guidance in these experiments.

The resistor network under study in these tests is shown schematically in Figure II-1. There are three 10,000 ohm resistors, three 24,000 ohm resistors, and one 150,000 ohm resistor included in this network. They differ from

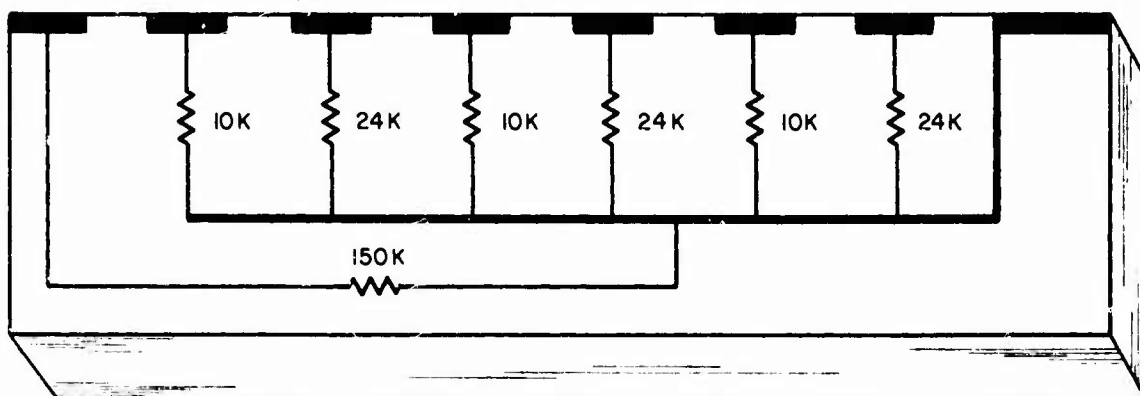


FIG. II - I SCHEMATIC REPRESENTATION OF RESISTOR NETWORK

each other only by the geometry (length/width ratio of the resistor strip) required to provide the range of values. All of the resistor strips have identical width (0.004 inch) and so it is the length that is varied to obtain the resistance range.

These networks were deposited by vacuum evaporation of a length of nichrome wire wound upon a resistance-heated tungsten filament. The substrates used were two kinds, soda lime glass and Corning 7059 borosilicate glass. In all but two groups tested, the resistor patterns were formed by photo-resist etching of the film after deposition. The interconnecting conductors were deposited onto the nichrome after the etching process had been completed. In the remaining two cases, a metal mask had been used to form the resistor pattern during deposition. Here the interconnecting conductors were deposited before the nichrome film. All but two of the network-sets were finished by coating with a protective material, ranging from silicon monoxide to an epoxy paint.

Two testing procedures were used to generate these data. In all but one of the tests the circuit in Figure II-2 was used. The 29.4 volt supply was applied to the resistors, without cycling, during the entire test. From the resistor geometry we can calculate the power density in each resistor during test. Thus:

$$p = \frac{P}{A} = \frac{V^2}{Rlw}$$

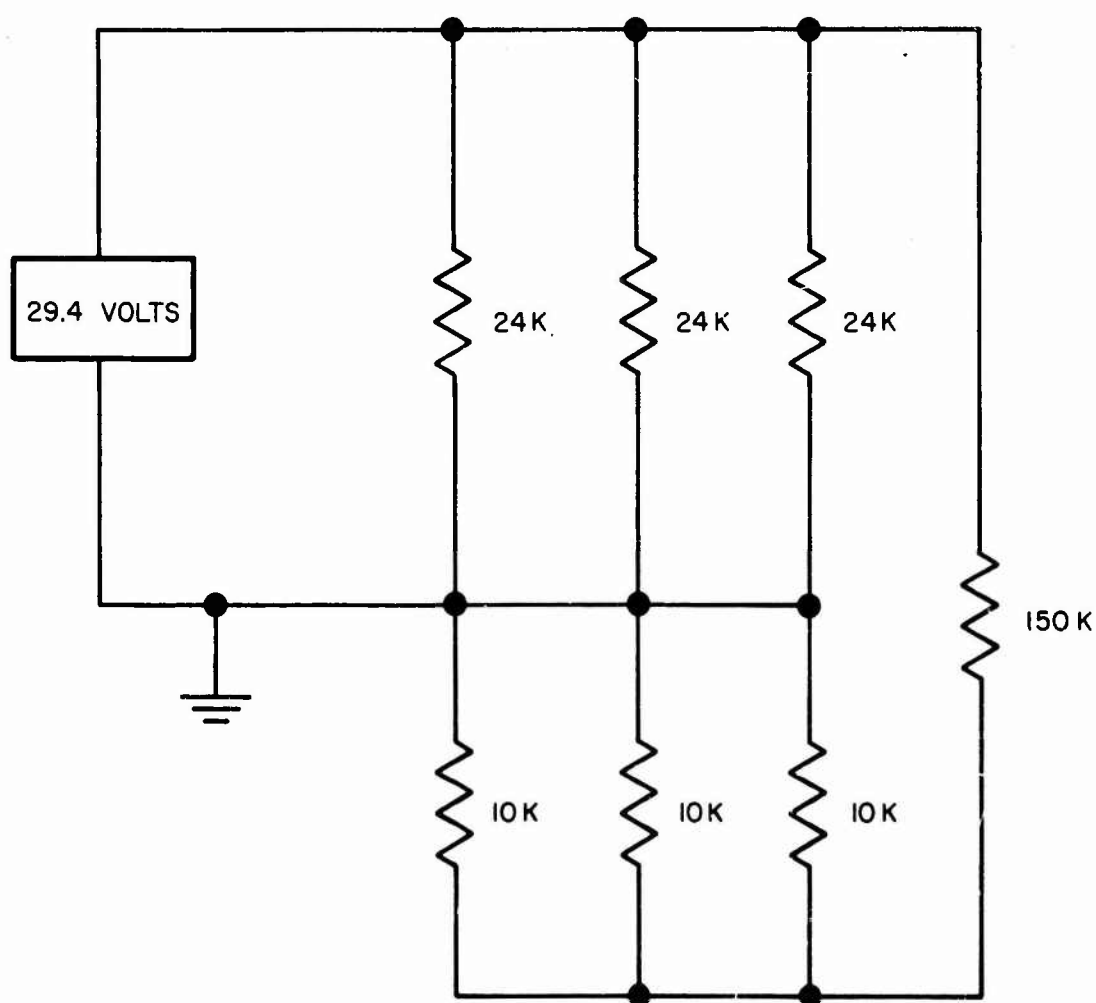


FIGURE II-2 STANDARD LIFE TEST AMBIENT = 70°C

where V is applied voltage, R is the resistor value,  $l$  is length and w is width of the resistor film. For each resistor value we have then

$$(R = 10 \text{ K}\Omega) \quad p = \frac{(29.4 \cdot \frac{3.33^*}{153.33})^2}{10^4 \times 1.33 \times 10^{-1} \times 4 \times 10^{-3}} = 7.62 \frac{\text{watts}}{\text{in}^2}$$

\* Equivalent of three 10 K resistors in parallel.

$$(R = 24 \text{ K}\Omega) \quad p = \frac{(29.4)^2}{2.4 \times 10^4 \times 3.2 \times 10^{-1} \times 4 \times 10^{-3}} = 28.2 \frac{\text{watts}}{\text{in}^2}$$

$$(R = 150 \text{ K}\Omega) \quad p = \frac{(29.4 \cdot \frac{150}{153.33})^2}{1.5 \times 10^5 \times 2 \times 4 \times 10^{-3}} = .69 \frac{\text{watts}}{\text{in}^2}$$

Thus, it can be seen that, in this test, almost two orders of magnitude separate the power dissipation density of the 24 K $\Omega$  and 150 K $\Omega$  resistor. One would therefore expect to see considerable differences in behavior in the corresponding resistor test data.

In Figure II-3 are plotted the resistance versus time data of each resistor in a sample network under the standard test conditions. Bear in mind that the order of increasing dissipation, and therefore the order of increasing film temperature, is 150 K, 10 K, and 24 K. From these data it seems that the highest power density results in the most negative-going resistance. This is true, in general, throughout the data for this test, although not always to the same extent.

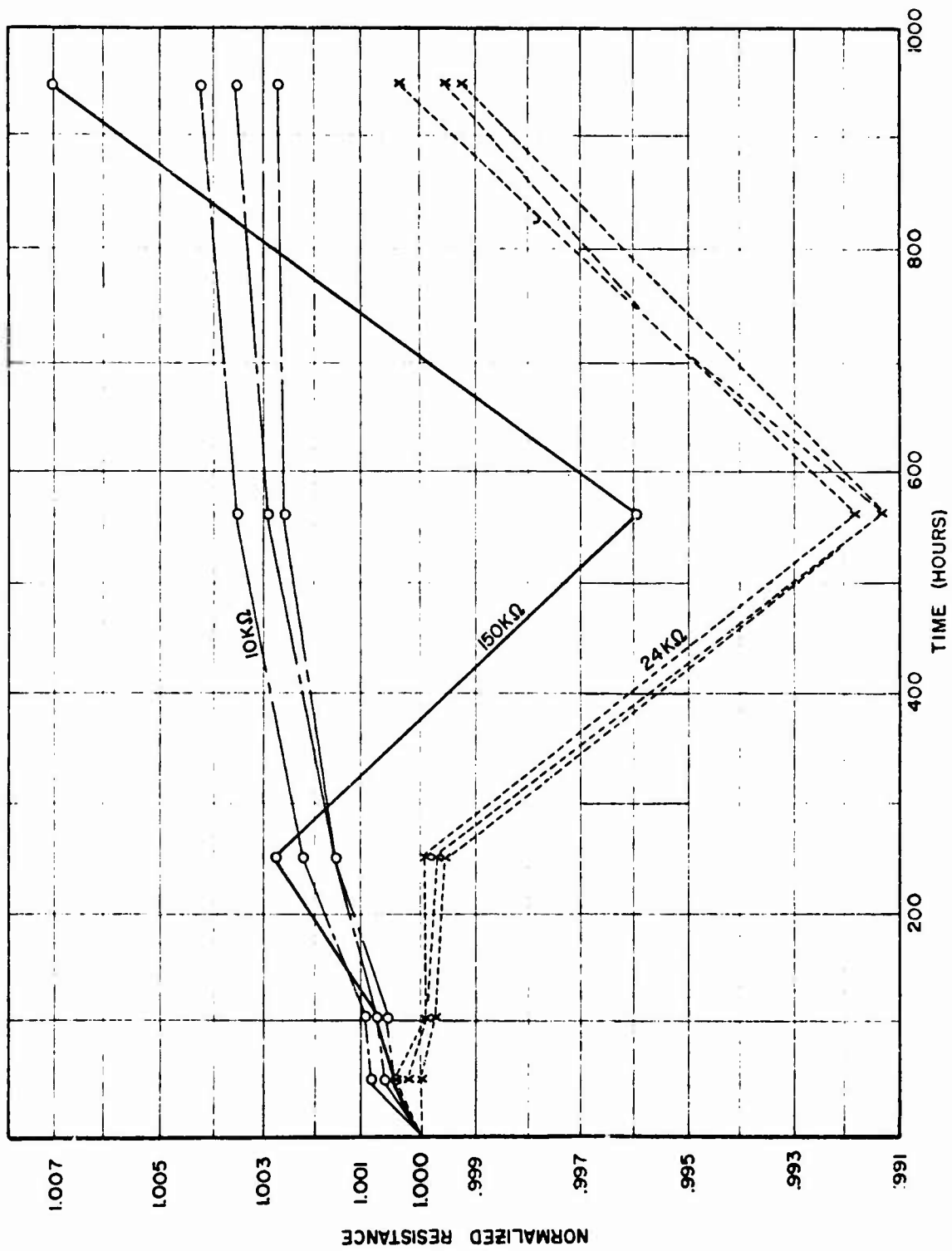


FIG. II-3 RESISTANCE VS. TIME - DATA FOR "STANDARD LIFE TEST"



If oxidation were the primary mechanism causing resistance change in these films, one would see a monotonically increasing function of time versus resistance. Clearly, however, there is at least one mechanism which brings about a decrease in film resistance and this mechanism is a rather strong function of temperature. One possible mechanism is the relaxation of mechanical stress in the film. The atoms in the film move relative to the substrate, seeking the lowest energy state and reducing the stress caused by the bonding forces between film and substrate. The mobility of these atoms is strongly affected by temperature as it is thermal agitation which is responsible for their motion. It is difficult to explain, however, why the films which show the greatest effect from this mechanism, or mechanisms, are at opposite ends of the power density spectrum. There is the possibility that a systematic error was introduced at the 511 hour point in the test; an error perhaps related to a scale change. Raising these points to lie on a smooth curve connecting the 260 hour point with the 980 hour point would place the data in a more logical relationship. But this is questionable procedure at best, and casts doubt on the other data as well. During the course of the remainder of the program these data will be given statistical analysis in order to eliminate, if possible, any systematic errors.

In Figure II-4 are plotted the data of a similar resistor network subjected to a cycling test in which power was applied for a period of time and then removed. The schematic drawing of this test setup is shown in Figure II-5. In this test the power dissipation in each of the 10 K and 24 K resistors was more nearly equalized, differing by about 20%. The dissipation in the 150 K resistor, however, was again smaller by a factor of 15. The actual power density for each resistor during the "2N" portion of the cycle was (10K) 94 watts/in<sup>2</sup>, (24K) 117 watts/in<sup>2</sup>, (150K) 6.25 watts/in<sup>2</sup>. The four hour cycle for the test is given in Table II-1.

In this set of data, it is not possible to see any dependence on the power density, or temperature, for all but two curves lie within a narrow range of values spanning only 0.1% which probably can be considered within experimental error. The two exceptions show quite erratic behavior and indicate possible fabrication imperfections.

We will continue to analyze the data, and any others that we receive prior to the end of the program, in order to extract important trends and to correlate with our own experimental results in the forming of a model. The manufacturer has also indicated that he will supply us with some sample nichrome films with which we can obtain a chemical analysis of typical films produced in his facilities. These films have not yet been received but we will follow up on them.

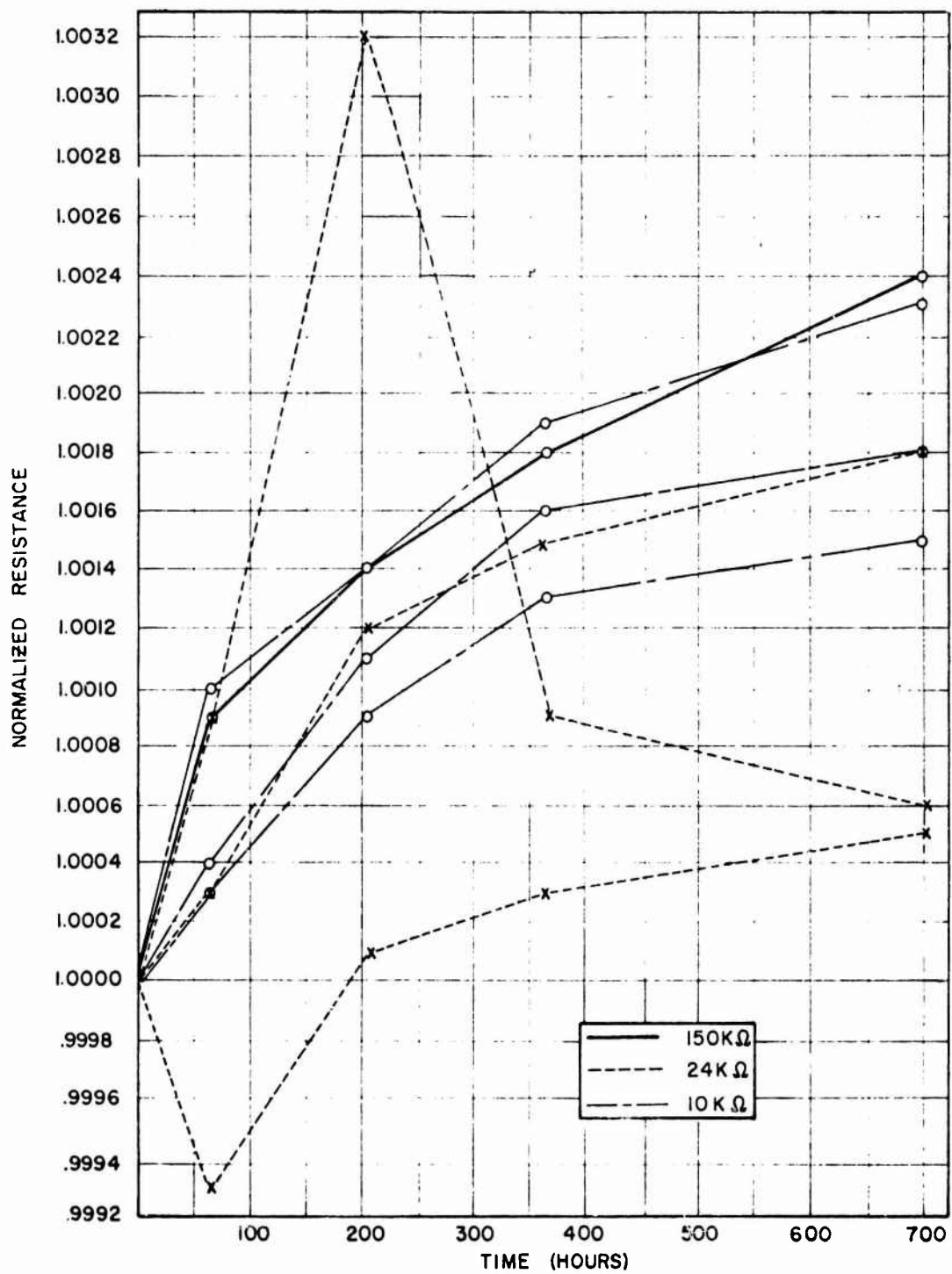


FIG. II-4 RESISTANCE VS. TIME — DATA FOR "SPECIAL LIFE TEST"

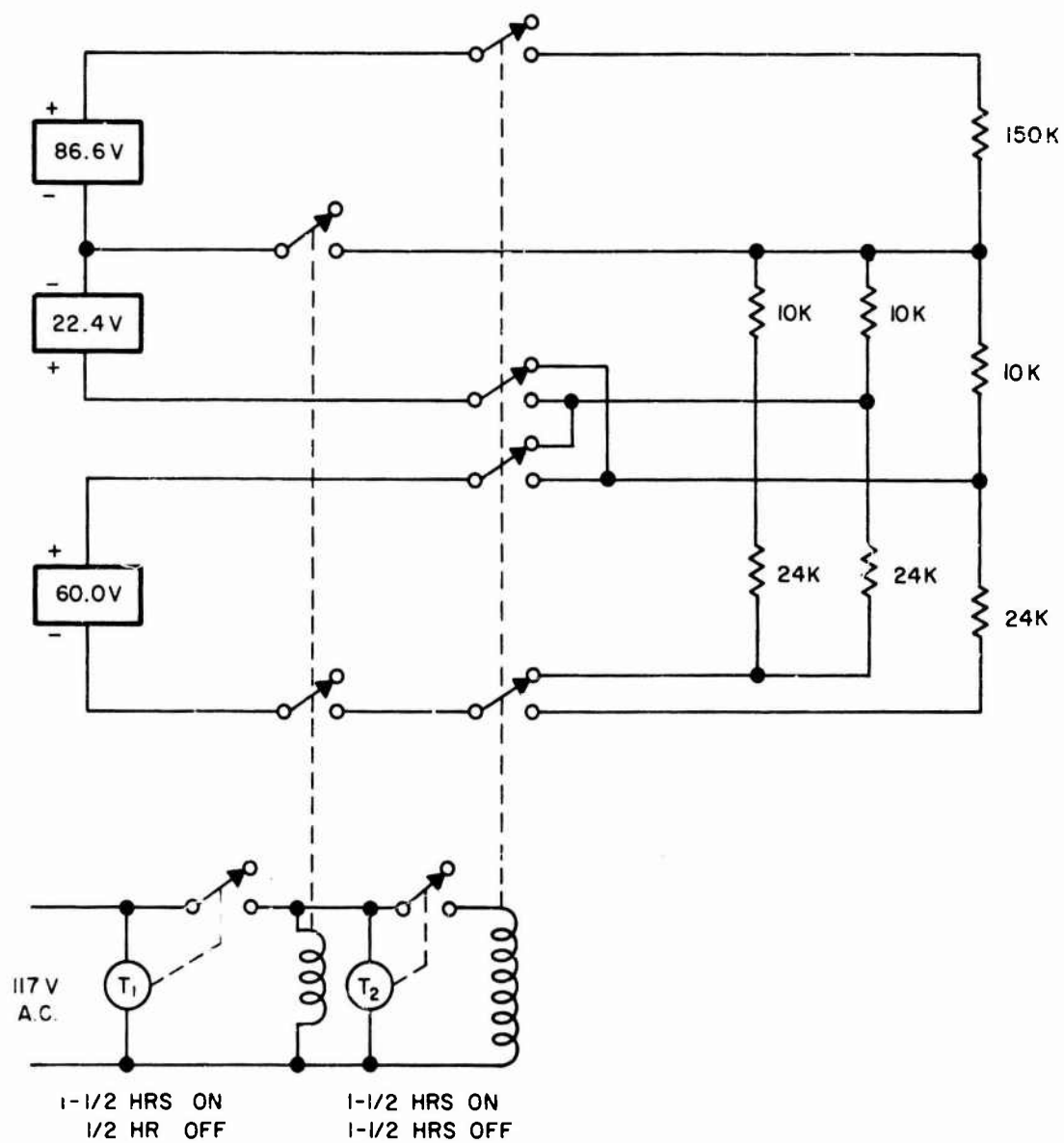


FIGURE II-5 SPECIAL LIFE TEST

### III. MATHEMATICAL TREATMENT OF MATRIX II DATA

In TDR-1 of this contract, a technique was described to determine whether the IRC data could be regrouped so that cells with nearly similar effective temperature could be combined. This would have enabled us to stratify the data by initial resistance and batch designations and yet obtain adequate sample sizes for the kind of analysis contemplated. It was found that the regrouping could not be done.

It was obvious, then, that we must use analysis techniques which permit inferences to be drawn about a number of questions as though the entire test was run to answer each question alone. The analysis of factorial designs of experiment is an example. The approach described in references (1, 2 and 3) was suggested, and is briefly described below.

The approach to be used allows us to construct models on all levels from the purely empirical to those based on rigorous derivations from theory. Although the knowledge and techniques presently available are still quite rudimentary, they represent a considerable advance in the state-of-the-art, and are such that revealing information about a physical situation can be obtained with an extremely modest expenditure of effort.

A few of the ideas involved have been used in preliminary analysis of some of the IRC Matrix II data.

Let  $R$  be the resistance of a resistor, and suppose that there is an unknown function,  $h$ , which gives  $R$  as a function of the environmental variables:

$$R = h(R_0, P, T, t),$$

where  $R_0$  is the initial resistance,  $P$  the power,  $T$  the temperature, and  $t$  the time of observation measured from the start of the test. Expanding this in Taylor's Series in  $t$  about the arbitrary value  $\bar{t}$ , we have

$$R = h(R_0, P, T, \bar{t}) + \left[ \frac{\partial h}{\partial t} \right]_{\bar{t}} (t - \bar{t}) + \left[ \frac{\partial^2 h}{\partial t^2} \right]_{\bar{t}} (t - \bar{t})^2 + \dots,$$

or in more convenient notation,

$$R = a_0 + a_1 (t - \bar{t}) + a_{11} (t - \bar{t})^2 + a_{111} (t - \bar{t})^3 + \dots$$

Data from 480 resistors were used to estimate the first four coefficients ( $a_0$ ,  $a_1$ ,  $a_{11}$ , and  $a_{111}$ ) in this expansion. These data were obtained by randomly selecting two resistors from each of the 240 possible combinations of 5 levels of  $R_0$  (100k $\Omega$ , 10 k $\Omega$ , 1k $\Omega$ , 150 $\Omega$ , 100 $\Omega$ ), 3 levels of percent rated power,  $P$ , (50, 100, 300), 4 levels of  $T$  in degrees centigrade (25, 78, 175, 225), and 4 batches (A, B, C, D). Estimation was done resistor by resistor, so that estimates of  $a_0$ ,  $a_1$ ,  $a_{11}$  and  $a_{111}$  were obtained for each of the 480 resistors.

Next, Taylor's series expansions of each of the coefficients,  $a_0$ ,  $a_1$ ,  $a_{11}$  and  $a_{111}$  were developed about the arbitrary

points  $\bar{R}_0$ ,  $\bar{P}$ ,  $\bar{T}$  and  $\bar{b}$ , where  $b$  refers to batch. The inclusion of  $b$  in this expansion can be justified by a statistical argument, although it is not, admittedly, a continuous variable subject to Taylor's theorem. Such justification will not be given here. The Taylor's series expansions look like

$$\begin{aligned} a = & c_0 + c_1 (R_0 - \bar{R}_0) + c_2 (P - \bar{P}) + c_3 (T - \bar{T}) + c_4 (b - \bar{b}) + \\ & c_{11} (R_0 - \bar{R}_0)^2 + c_{22} (P - \bar{P})^2 + c_{33} (T - \bar{T})^2 + \\ & c_{44} (b - \bar{b})^2 + \dots \\ & + c_{12} (R_0 - \bar{R}_0) (P - \bar{P}) + c_{13} (R_0 - \bar{R}_0) (T - \bar{T}) + \dots \\ & + c_{112} (R_0 - \bar{R}_0)^2 (P - \bar{P}) + \dots + c_{244} (P - \bar{P}) (b - \bar{b})^2 + \dots \end{aligned}$$

For each of the  $a$ 's, the 480 values were used to estimate the  $c$ 's. Readily available computer programs did not have a large enough capacity to estimate all possible  $c$ 's; consequently, only those terms involving one or two of the variables  $R_0$ ,  $P$ ,  $T$ , and  $b$  were estimated.

There are two important things that these estimates reveal. The first is that the Taylor series coefficients for many of the terms are proportional; the  $c$ 's for  $a_0$  are approximately 3 times the  $c$ 's for  $a_1$  and approximately one-fourth the  $c$ 's for  $a_{11}$ . Moreover, the  $c$ 's for  $a_{111}$  are not significantly different from zero. This implies that the

functional dependence of R on the variables must be independent of t. In fact, the functional dependence must be of the form

$$R = h(R_0, P, T, t) = k R_0 + f(R_0, P, T) g(t), \quad (1)$$

where k is a constant. In addition, if one considers R to be also a function of batch, b, then the functional dependence must have the form

$$R = k R_0 + u(R_0, P, T, b) v(t) . \quad (2)$$

This functional dependence is clearly different from that which has heretofore been used by IITRI.

The second important observation that may be made from the c's is that those c's involving b are not statistically different from zero. That is, the batch to batch variation is not significantly different from the variation between nominally identical specimens.

Finally, then, our functional form must be independent of batch (at least for whatever batch designation meant in the IRC data) and the function g(t) in equation (1) is either quadratic in t or at least well approximated by a quadratic in t.

The next step is to utilize this information to derive a candidate model either from first principles or else from phenomenological observations in a manner similar to that of Cushner, as reported in (4). Then, instead of



estimating the values of the Taylor's series derivatives from data we would calculate parameter values from the functional form. The parameters would be fitted to each resistor. Thus, for a sample of 480 resistors we would have 480 estimates of each parameter. These estimates would now constitute our statistical sample. From the analysis we could infer whether or not the model was adequate and, if inadequate, how it should be modified.

The model building philosophy we adopted is that the model should be based on logical assumptions and/or experimental observations but should not involve the complex microscopic processes except as a starting point for the derivation.

Two models were derived. The first is patterned after Cushner as reported in a recent IRC report. We also utilized the results of our analysis of IRC's Matrix II data given above. In contrast to Cushner, we did not assume that percent change of resistance is independent of initial resistance value. The second model is based on experimental evidence and other information reported in our Final Report, Contract AF 30(602)-3251<sup>(5)</sup>, and Levinson and Stewart's paper<sup>(6)</sup>.

We assume the change in resistance as a function of time is distributed thus:

$$\Delta R = \Delta R_T + \Delta R_i + \Delta R_v ,$$

where

$\Delta R_T$  = resistance change due to absolute temperature,

$\Delta R_i$  = resistance change due to electricity flow,

$\Delta R_v$  = resistance change due to gradient of the potential.

As stated above, our analysis of IRC data indicated that

$R(t)$  is of the form  $k R_o + h(R_o, P, T) g(t)$ .

Let

$$\Delta R_T = R_o^a C_1 e^{-\frac{E}{kT}} g(t)$$

where

$k$  = Boltzmann's constant,

$T = T_A + 30 P$  (Cushner),

$T_A$  = ambient temperature ( $^{\circ}K$ ),

$P$  = fraction of rated power,

$R_o$  = initial resistance,

$g(t)$  = a function of time alone.

Let

$$\Delta R_i = R_o^{b-1/2} C_2 P^{1/2} g(t) .$$

Let

$$\Delta R_v = R_o^c C_3 P g(t) .$$

Then we have

$$\Delta R = (C_1 R_O^a e^{-\frac{E}{kT}} + C_2 R_O^{b-1/2} P^{1/2} + C_3 R_O^c P) g(t) ,$$

or, since  $\Delta R = R(t) - R_O$  ,

$$R(t) = R_O + (C_1 R_O^a e^{-\frac{E}{kT}} + C_2 R_O^{b-1/2} P^{1/2} + C_3 R_O^c P) g(t) .$$

It is to be noted that our analysis of the IRC data indicates that  $g(t)$  is either a quadratic or well approximated by a quadratic.

Cushner states that his model is applicable to negative resistance changes (i.e., decreasing resistance), only. Since we have patterned the above model after Cushner, it may be reasonable to impose this restriction here, too.

For our second model we assume the mechanisms of degradation are precipitation and oxidation. We begin with precipitation. From (5) we have the resistivity of bulk metals given by

$$\rho = \rho_O + \rho_T = \frac{m}{Ne^2} (n_O + n_T) ,$$

where

$m$  = effective electron mass,

$N$  = density of free electrons,

$e$  = electronic charge,

$n_O$  = number of collisions per second with lattice imperfections

$n_T$  = number of collisions per second with vibrating lattice points.

$n_0$  is independent of temperature and  $n_T$  varies linearly with temperature.

The resistivity due to lattice imperfections is given by

$$\rho_0 = \left( \frac{m}{Ne^2} \right) \left( \frac{vx}{\Omega_0} \right) A ,$$

where

$v$  = electron velocity,

$\Omega_0$  = atomic volume,

$A$  = effective cross section of each foreign atom,

$x$  = fractional concentration of solute atoms in solid solution.

In general, thin films contain a high density of lattice imperfections so that  $\rho_0$  may dominate and we may neglect  $\rho_T$  (this is over simplified, see reference (5), pages 15, 16, and 17).

In the above expression for  $\rho_0$  only  $x$  will be affected by time and thus

$$\rho_0(t) = C x(t) ,$$

where  $C$  is a constant whose value depends on the constituents of the alloy.

For thin films, according to Fuchs, if  $\ell$  is less than  $c$  then

$$\rho = \rho_0 \left( 1 + \frac{3}{8} \ell/c \right) ,$$

where

$\rho_0$  = bulk sheet resistivity,

$\ell$  = mean free path of electrons in the metal,

$c$  = film thickness.

Then

$$\rho(t) = \rho_0 (1 + 3/8 \ell/c) = C_0 x(t) (1 + 3/8 \ell/c) .$$

Now let us assume the precipitation process is a diffusion of solute atoms to nucleation sites which, in turn are assumed to be lattice imperfections. Let  $x_0$  be the initial concentration of solute atoms in solid solution. Then it appears reasonable to postulate:

$$x(t) = x_0 - N_c D e^{-\frac{E}{kT}} g(t)$$

where

$N_c$  = number of nucleation sites and is a function of film thickness

$D$  = a diffusion coefficient,

$E$  = an activation energy,

$k$  = Boltzmann's constant,

$T$  = temperature ( $^{\circ}K$ ),

$t$  = time.

(It is to be noted that this model for precipitation applies only for  $T$  less than the equilibrium temperature and  $t_i \leq t \leq t_E$ ;  $t_i$  = time of onset and  $t_E$  = time of completion of precipitation and both are functions of temperatures and composition of the alloy.)

Hence we have

$$\rho(t) = C \left[ x_o - D_o e^{-\frac{E}{kT} g(t)} \right] (1 + 3/8 \ell/c), \text{ where } D_o = N_c D.$$

Total resistance may be given by

$$R(t) = \frac{\rho(t)L}{cd},$$

for a configuration of rectangular cross section with  $c$  = thickness,  $d$  = width, and  $L$  = length of resistive material.

Then

$$R(t) = \frac{L}{d} C \left[ x_o - D_o e^{-\frac{E}{kT} g(t)} \right] \left( \frac{1}{c} + 3/8 \ell/c^2 \right).$$

If oxidation proceeds uniformly, we may apply Fromhold's space charge limited relation (see references 5 and 6).

$$y(t) = \gamma^2 \left( 1 - e^{-\frac{t}{w}} \right),$$

where

$\gamma$  = limiting thickness; a function of temperature  
and oxygen partial pressure,

$w$  = a time constant, a function of temperature  
and oxygen partial pressure,

$y(t)$  = oxide thickness at time  $t$ .

Uniform oxidation will reduce the effective film thickness.

Thus,

$$R(t) = \frac{L}{d} C \left[ x_o - D_o e^{-\frac{E}{kT} g(t)} \right] \left[ \frac{1}{c-y(t)} + \frac{3/8 \ell}{(c-y(t))^2} \right].$$

These two models are presented side by side, for comparison below. It remains for the project team to discuss these models with a view toward examining their validity and utility.

The model patterned after Cushner is

$$R(t) = R_0 + (C_1 e^{-\frac{E}{kT}} R_0^a + C_2 P^{1/2} R_0^{b-1/2} + C_3 P R_0^c) g(t)$$

where

$R(t)$  = resistance value at time  $t$ ,

$R_0$  = initial resistance,

$E$  = activation energy,

$k$  = Boltzmann's constant,

$P$  = fraction of rated power,

$T = T_A + 30P$  (from Cushner),  $T$  and  $T_A$  in  $^{\circ}K$ ,

$a, b, c, C_1, C_2$  and  $C_3$  are constants,

$g(t)$  = function of time alone (see E6042-5).

The second model is

$$R(t) = C \left[ x_0 - D_0 e^{-\frac{E}{kT}} g(t) \right] \left[ \frac{1}{c-y(t)} + \frac{3/8 \ell}{(c-y(t))^2} \right],$$

where

$R(t)$  = resistance at time  $t$ ,

$C, D_0$  = constants,

$x_0$  = fractional concentration of solute atoms  
at time zero,

$c$  = average film thickness,

$E$  = activation energy,  
 $k$  = Boltzmann's constant,  
 $T$  = effective film temperature,  
 $g(t)$  = a function of time alone,  
 $\lambda$  = mean free path of electrons in the metal,  
 $y(t) = Y^2 \left[ 1 - \exp \left( -\frac{t}{w} \right) \right]$  ,  
 $Y$  = limiting thickness of oxide and is a  
function of temperature and oxygen pressure,  
 $w$  = a time constant and is a function of temperature and oxygen pressure.

#### IV. EXPERIMENTAL EFFORTS

Since the last technical report, our experimental efforts have been greatly reduced, partly because of regularly scheduled vacations and partly due to relocation of our facilities into new quarters. Much of the remaining time was used to construct the needed apparatus for flash evaporation and in designing the subsequent experiments.

In the early part of the program we performed a number of depositions designed to determine the range of compositions one could expect to find through the cross section of typical filament evaporated nichrome films. The range of composition encompassed in these films extended from 50% Ni - 50% Cr to 95% Ni - 5% Cr,<sup>5</sup> with the layers which had been deposited earliest being the richest in



chromium. If this type of composition variation is found in commercial resistors, it is essential to know the dependence on composition of the rates at which the degradation mechanisms operate. For as a mechanism such as oxidation proceeds through the film and encounters these different compositions, its rate will be altered according to this dependence. Thus, any physical modeling effort must take into account these factors.

But in order to systematically study these effects, one must be able to prepare films of alloys of representative compositions which are uniform throughout their thickness. With alloys whose constituents have radically different vapor pressures, this is difficult to accomplish by vacuum evaporation. Cathode sputtering is capable of depositing stoichiometric films but the films will differ in other characteristics from thermally evaporated films. Uniformity can be closely approximated, however, by flash evaporating fine powders of the subject alloy.

Flash evaporation consists chiefly of the dropping of fine particles onto a filament or crucible which is held at a temperature at which the alloy particle will completely evaporate on contact with the crucible. By controlling the rate at which the particles are allowed to drop onto the crucible, the rate of alloy evaporation and, consequently, the film thickness can be controlled.

An apparatus was constructed for carrying out the flash technique and is depicted schematically in Figure IV-1. A large tantalum funnel-like dish is attached to a curving chute, the point of which is directly over a smaller funnel. The latter is placed so that its discharge end is directly over the crucible. A magnetic spiral spring is spot welded to the large dish and placed in close proximity to a solenoid. The solenoid is actuated by a d-c supply which is interrupted by a switch actuated by a rotating cam. The pulsating d-c then imparts, through the magnetic spring, a vibration to the dish-spout assembly. Grains of alloy which are placed in the large dish before evaporation, are shaken into the chute and finally are dropped through the smaller funnel to the crucible. The apparatus is constructed such that there is minimum obstruction of the vapor stream.

Monitoring of the film thickness is done indirectly by measuring the resistance of one of the elements being deposited. A pair of copper wires is prepared by bonding to their ends an indium ball about one millimeter in diameter. These indium pellets are then placed in contact with the silver contacting lands for the resistor by suitably mounting the copper wire in a holder. Electrical contact is brought to the outside of the vacuum chamber where an ohm-meter is used to monitor the resistance.

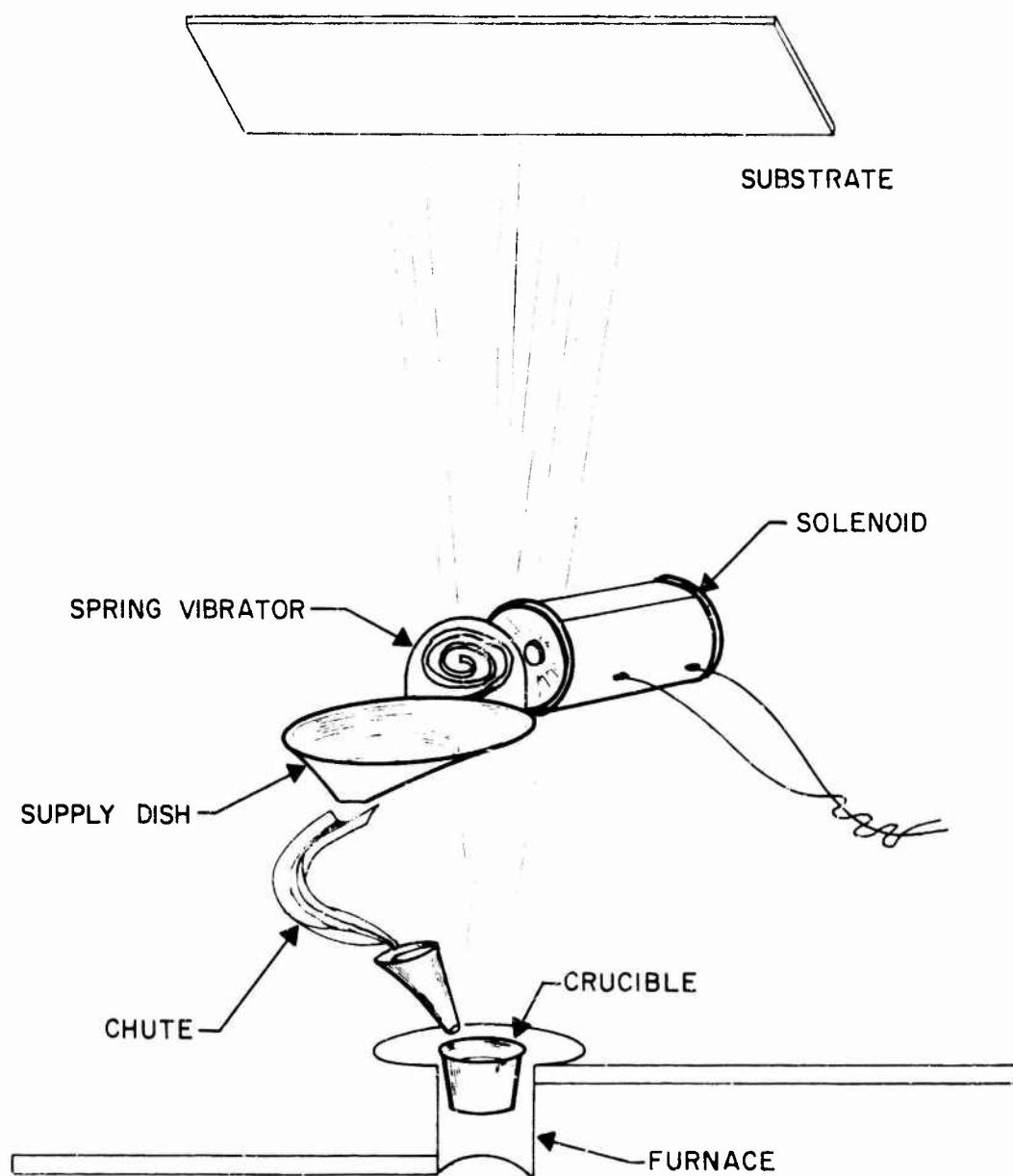


FIG. IV-1 FLASH EVAPORATION APPARATUS

In fact, we have decided to make the initial resistance ( $R_0$ ) of these elements common throughout the experiment. This is because films whose thickness is several hundred angstrom units should show little variance in behavior with thickness, per se. It is the composition change which accompanies the thickness variation which, we believe, is responsible for the major behavioral differences. But because of the difficulty in predicting the precise value of resistivity for these films, it is impractical, in these experiments, to try to keep thickness invariant through resistance monitoring.

The alloys for these experiments are made by an arc melting process. A quantity of nichrome wire is placed in a crucible along with the required amount of pure chromium to form the desired alloy. An arc is struck between two tungsten electrodes and transferred to the crucible containing the alloy constituents. The process is repeated several times to insure a homogeneous pellet. The alloys chosen for this program were 80 - 20 (Nichrome V), 60 - 40, 40 - 60, and 20 - 80 nickel - chromium. These extend into the chromium-rich end of the range beyond those compositions found in our earlier experiments and in the first series of tests only the first three of the above alloys will be deposited. The actual measured weight per cent of the constituents

of each of these alloys is (1) 58.7% Ni - 41.3% Cr, (2) 39.4% Ni - 60.5% Cr, (3) 21.4% Ni - 78.5% Cr, in addition to the Nichrome V whose actual measured composition is 78% Ni 19% Cr.

As of the end of the reporting period, the flash deposition apparatus had been constructed, the alloys were in the preparation stage, and the actual experiment had been designed. Actual film depositions are to begin early in the next reporting period.

The experiment design is a "fixed effects" factorial. This means that the independent variables of the experiment are controlled and are not random variables. The independent variables and their values are presented in Table IV-1. The experiment will involve a total of 36 resistors. By uniformity is meant the manner in which the composition varies through the cross-section of the film. A "non-uniform" film is one which has been deposited from a wire filament and is subject to the type of variations discussed in reference 1. The "uniform film" will have been flash evaporated and should closely approach homogeneity. The initial resistance,  $R_0$ , of these films will not be a variable; it will remain constant throughout the experiment. The value of  $R_0$  has been selected to be 1000 ohms.

TABLE IV-1  
ACTIVATION ENERGY AND MODELING EXPERIMENT

<u>Variable</u>	<u>No. of Levels</u>	<u>Values of the Levels</u>
uniformity of film	2	1 non-uniform 2 uniform
composition	3	1 40% Ni 60% Cr 2 60 40 3 80 20
temperature (ambient)	3	1 100°C 2 200 3 300
power (applied voltage)	2	1 no power 2 25 volts d.c.

NOTE: Each resistor will have the same nominal initial resistance and the oxygen partial pressure will be one of mm of mercury.

Three tube ovens will be used, one each at 100°C, 200°C, and 300°C. Each oven will contain twelve resistors, six of which will be energized with 25 volts d-c, which will cause them to dissipate 25 watts/in<sup>2</sup>, a value close to that encountered in the manufacturers data referred to in the first part of this report. The tubes will be filled to an oxygen partial pressure of 1 Torr, another constant throughout the experiment.

We assume, in these experiments, that third order, and higher, interactions between the experimental variables

are negligible. With this assumption there will be sixteen degrees of freedom available at each time of measurement for estimating error. This is an adequate number since we are measuring resistance value, and not time to failure.

In order to investigate the characteristics of the mathematical model for these resistors, the data will be analyzed in the same manner as was the Matrix II data, as described in Section III. This analysis involved a Taylor's Series expansion and the empirical determination of the partial derivatives involved. It will be recalled that, from this analysis, it was deduced that the Evanohm resistor is described by a relationship of the form:

$$R(t, T) = R_0 + f(R_0, P, T) g(t)$$

where

$R_0$  = initial resistance,

$P$  = per cent of rated power,

$T$  = temperature,

$t$  = time,

$f(R_0, P, T)$  = an unspecified function,

$g(t)$  = function of time only and at most of degree 2.

The data from our experiments will be carried a step further. They will be used to estimate the activation energy of the physical processes involved and from these estimates a physical model will be postulated. This physical equation will be compared to the Taylor Series expansion.

## V. SUMMARY

We have discussed in this report the activities of the IITRI staff involved in the collection and analysis of resistor life test data and experimental investigation of resistor failure mechanisms. Life test data on more than 1000 individual resistors were obtained from a manufacturer of nichrome thin film resistor networks. These data covered more than 1000 hours of testing under various applied power but only one ambient temperature, 70°C. These data will be useful in evaluating a physical model derived from experiment, but cannot be used, as was the Matrix II data, in empirically determining the form of the mathematical expression.

We have worked out a procedure by which data from a statistically designed life test experiment can be programmed for the computer and fit to a Taylor's series expansion. The coefficients obtained by expansion of the Matrix II data on IRC Evanohm resistors indicate that a model for this species of resistor must contain a factorable function of time. Moreover, the function can be closely approximated by a quadratic in time. It is also evident that there is little or no dependence of the model on variations from batch to batch.

Finally, the experimental activities were directed toward performing a statistically designed experiment from which an empirical model could be obtained as well as the rate constants and activation energies of the



physical mechanisms operating on the resistors. Part of the effort leading up to these experiments was the construction and de-bugging of flash evaporation apparatus to be used for the production of homogeneous nickel-chrome alloy films of various compositions. These will be employed in the experiments to determine the dependence on composition of the rate constants of failure mechanisms.

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<p>This report describes some results of research on failure mechanisms in thin metal film resistors. The effort is to develop mathematical expressions for these mechanisms which can be assembled into a comprehensive model for this class of device.</p> <p>The report describes the early results of analysis of nichrome resistor life test data obtained from a manufacturer of resistive networks. Also presented are the results of computer analysis of Matrix II life test data on Evanohm resistors indicating that the model must contain separable functions of time and the experimental variables (stresses, initial resistance, etc.). The experimental work described involves an attempt to statistically design an experiment to give the maximum number of degrees of freedom in estimating error and in constructing a model.</p>		

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